2.5B: Flagella

Skills to Develop

1. Describe the basic structure of a bacterial flagellum and state its function.
2. State what provides the energy for bacterial flagellar rotation.
3. Define the following flagellar arrangements:
   a. monotrichous
   b. lophotrichous
   c. amphitrichous
   d. peritrichous
   e. axial filaments
4. Define taxis.
5. Compare and contrast how bacteria with peritrichous flagella and bacteria with polar flagella carry out taxis.
6. State how bacterial flagella may play a role in the initiation of innate immune defenses.
7. Briefly describe how bacterial flagella and chemotaxis may play a role in the pathogenicity of some bacteria.

Highlighted Bacterium

1. Read the description of *Treponema pallidum* and match the bacterium with the description of the organism and the infection it causes.

TPS Exercise

Many pathogenic bacteria that infect the intestinal tract have flagella.

1. Why might having flagella better enable those bacteria to cause disease?
2. Our defense cells have a surface PRR called TLR-5 that recognizes bacterial flagellin. In terms of preventing infection, why is this an advantage?

3. Most pathogenic spirochetes such as Treponema pallidum and Borrelia burgdorferi disseminate from the original infection site. How are they able to do this?

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**Structure and Composition of Flagella**

A bacterial flagellum has three basic parts: a filament, a hook, and a basal body.

![Diagram of a flagellum](https://bio.libretexts.org/Bookshelves/Microbiology/Book%3A_Microbiology_(Kaiser)/Unit_1%3A_Introduction_to_Microbiology%2FChapter_4%3A_Bacterial_Motility_and_Approaches_to_Molecular_Motor_Science%2F4.B%3A_Flagellar_Consortium%2F4B.1.png)

*Figure 4B.1: A flagellum (plural: flagella) is a long, slender projection from the cell body, whose function is to propel a unicellular or small multicellular organism. The depicted type of flagellum is found in bacteria such as E. coli and Salmonella, and rotates like a propeller when the bacterium swims. The bacterial movement can be divided into 2 kinds: run, resulting from a counterclockwise rotation of the flagellum, and tumbling, from a clockwise rotation of the flagellum.*

*Image used with permission from Wikipedia (LadyofHats)*

1. The filament is the rigid, helical structure that extends from the cell surface. It is composed of the protein flagellin arranged in helical chains so as to form a hollow core. During synthesis of the flagellar filament, flagellin molecules coming off of the ribosomes are transported through the hollow core of the filament where they attach to the growing tip of the filament causing it to lengthen. With the exception of a few bacteria, such as *Bdellovibrio* and *Vibrio cholerae*, the flagellar filament is not surrounded by a sheath (see Figure 1).

2. The hook is a flexible coupling between the filament and the basal body (see Figure 1).

3. The basal body consists of a rod and a series of rings that anchor the flagellum to the cell wall and the cytoplasmic membrane (see Figure 1). Unlike eukaryotic flagella, the bacterial flagellum has no internal fibrils and does not flex. Instead, the basal body acts as a rotary molecular motor, enabling the flagellum to rotate and propel the bacterium through the surrounding fluid. In fact, the flagellar motor rotates very rapidly. (Some flagella can rotate up to 300 revolutions per second!)

The MotA and MotB proteins form the stator of the flagellar motor and function to generate torque for rotation of the flagellum. The MS and C rings function as the rotor. (See Figure 1). Energy for rotation comes from the proton motive
force provided by protons moving through the Mot proteins along a concentration gradient from the peptidoglycan and periplasm towards the cytoplasm.

For More Information: Review of Proton Motive Force from Unit 7

- Electron micrograph and illustration of the basal body of bacterial flagella; Cover photo of Molecular Biology of the Cell, May 1, 2000.
- Animation of a rotating bacterial flagellum from the ARN Molecular Museum
- YouTube movie of the assembly and rotation of a bacterial flagellum

Bacteria flagella (see Figure 2 and Figure 3) are 10-20 µm long and between 0.01 and 0.02 µm in diameter.

Flagellar Arrangements (see Figure 4)

1. **monotrichous**: a single flagellum, usually at one pole
   - Scanning electron micrograph showing monotrichous flagellum of *Vibrio*; courtesy of CDC.

2. **amphitrichous**: a single flagellum at both ends of the organism

3. **lophotrichous**: two or more flagella at one or both poles
   - Scanning electron micrograph of *Helicobacter pylori* showing lophotrichous arrangement of flagella; from Science Photolab.com

4. **peritrichous**: flagella over the entire surface
   - Scanning electron micrograph of *Proteus vulgaris* showing peritrichous arrangement of flagella and pili; from fineartamerica.com

5. axial filaments: internal flagella found only in the spirochetes. Axial filaments are composed of from two to over a hundred axial fibrils (or endoflagella) that extend from both ends of the bacterium between the outer membrane and the cell wall, often overlapping in the center of the cell. (see Figure 5 and Figure 6). A popular theory as to the mechanism behind spirochete motility presumes that as the endoflagella rotate in the periplasmic space between the outer membrane and the cell wall, this could cause the corkscrew-shaped outer membrane of the spirochete to rotate and propel the bacterium through the surrounding fluid.
   - Axial filaments of the spirochete Leptospira; Midlands Technical College, Bio 255 course site

Functions

Flagella are the organelles of locomotion for most of the bacteria that are capable of motility. Two proteins in the flagellar motor, called MotA and MotB, form a proton channel through the cytoplasmic membrane and rotation of the flagellum is
driven by a proton gradient. This driving proton motive force occurs as protons accumulating in the space between the cytoplasmic membrane and the cell wall as a result of the electron transport system travel through the channel back into the bacterium's cytoplasm. Most bacterial flagella can rotate both counterclockwise and clockwise and this rotation contributes to the bacterium's ability to change direction as it swims. A protein switch in the molecular motor of the basal body controls the direction of rotation.

1. A bacterium with peritrichous flagella:

If a bacterium has a peritrichous arrangement of flagella, counterclockwise rotation of the flagella causes them to form a single bundle that propels the bacterium in long, straight or curved runs without a change in direction. Counterclockwise rotation causes the flagellum to exhibit a left-handed helix. During a run, that lasts about one second, the bacterium moves 10 - 20 times its length before it stops. This occurs when some of the flagella rotate clockwise, disengage from the bundle, and trigger a tumbling motion. Clockwise rotation causes the flagellum to assume a right-handed helix. A tumble only lasts about one-tenth of a second and no real forward progress is made. After a "tumble", the direction of the next bacterial run is random because every time the bacterium stops swimming, Brownian motion and fluid currents cause the bacterium to reorient in a new direction.

Movie of swimming *Escherichia coli* as seen with phase contrast microscopy.
Flagella are not visible with under phase contrast microscopy. Note runs and tumbles.
Courtesy of Dr. Howard C. Berg from the Roland Institute at Harvard.

Movie of motile *Escherichia coli* with fluorescent labelled-flagella #1.
This technique allows the flagella to be seen as the bacteria swim. Note some flagella leaving the flagellar bundle to initiate tumbling.
Courtesy of Dr. Howard C. Berg from the Roland Institute at Harvard.

Movie of motile *Escherichia coli* with fluorescent labelled-flagella #2.
This technique allows the flagella to be seen as the bacteria swim. Note some flagella leaving the flagellar bundle to initiate tumbling.
Courtesy of Dr. Howard C. Berg from the Roland Institute at Harvard.

Movie of tethered *Escherichia coli* showing that the bacterial flagella rotate.
Courtesy of Dr. Howard C. Berg from the Roland Institute at Harvard.

When bacteria with a peritrichous arrangement grow on a nutrient-rich solid surface, they can exhibit a swarming motility wherein the bacteria elongate, synthesize additional flagella, secrete wetting agents, and move across the surface in coordinated manner.

Movie of swarming motility of *Escherichia coli*.
Courtesy of Dr. Howard C. Berg from the Roland Institute at Harvard.

2. A bacterium with polar flagella:

Most bacteria with polar flagella, like the peritrichous above, can rotate their flagella both clockwise and counterclockwise. If the flagellum is rotating counterclockwise, it pushes the bacterium forward. When it rotates clockwise, it pulls the bacterium backward. These bacteria change direction by changing the rotation of their flagella.
**Video 4B.1:** Phase contrast movie of motile *Pseudomonas*. *Pseudomonas* has a single polar flagellum that can rotate both counterclockwise and clockwise but is not visible under phase contrast microscopy ([http://www.youtube.com/embed/EWj2TGsTQEi](http://www.youtube.com/embed/EWj2TGsTQEi)).

**Movie of *Spirillum volutans***, a spiral-shaped bacterium with a bundle of flagella at either end. Courtesy of Dr. Howard C. Berg from the [Roland Institute](http://www.youtube.com/embed/EWj2TGsTQEi) at Harvard.

Some bacteria with polar flagella can only rotate their flagellum clockwise. In this case, clockwise rotation pushes the bacterium forward. Every time the bacterium stops, Brownian motion and fluid currents cause the bacterium to reorient in a new direction.

**Movie of *Rhodobacter spheroides*** with fluorescent-labelled flagella. The flagellum can only rotate clockwise. Courtesy of Dr. Howard C. Berg from the [Roland Institute](http://www.youtube.com/embed/EWj2TGsTQEi) at Harvard.

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**Taxis**

Around half of all known bacteria are motile. Motility serves to keep bacteria in an optimum environment via taxis. Taxis is a motile response to an environmental stimulus. Bacteria can respond to chemicals (chemotaxis), light (phototaxis),

[Concept map for Bacterial Flagella](http://www.youtube.com/embed/EWj2TGsTQEi)
osmotic pressure (osmotaxis), oxygen (aerotaxis), and temperature (thermotaxis). Chemotaxis is a response to a chemical gradient of attractant or repellent molecules in the bacterium's environment.

- In an environment that lacks a gradient of attractant or repellent, the bacterium moves randomly. In this way the bacterium keeps searching for a gradient.
- In an environment that has a gradient of attractant or repellent, the net movement of the bacterium is towards the attractant or away from the repellent.

If a bacterium has a peritrichous arrangement of flagella, such as *Escherichia coli*, *Salmonella*, *Proteus*, and *Enterobacter*, counterclockwise rotation of the flagella causes them to form a single bundle that propels the bacterium in long, straight or curved runs without a change in direction. Clockwise rotation of some of the flagella in the bundle causes those flagella to be pushed apart from the bundle triggering a tumbling motion. Every time the bacterium tumbles it reorients itself in a new direction. In the presence of a chemical gradient, these movements become biased. When the bacterium is moving away from higher concentrations of repellents or towards higher concentrations of attractants the runs become longer and the tumbles less frequent.

Movie of tethered Escherichia coli Switching from clockwise rotation to counterclockwise rotation as attractant is added. Courtesy of Dr. Howard C. Berg from the Roland Institute at Harvard.

Most bacteria with polar flagella, such as *Pseudomonas aeruginosa*, can rotate their flagella both clockwise and counterclockwise. If the flagellum is rotating counterclockwise, it pushes the bacterium forward. When it rotates clockwise, it pulls the bacterium backward. These bacteria change direction by changing the rotation of their flagella. Some bacteria with polar flagella, such as *Rhodobacter sphaeroides*, can only rotate their flagellum clockwise. In this case, clockwise rotation pushes the bacterium forward. Every time the bacterium stops, it reorients itself in a new direction.

For More Information: Chemotaxis in *Escherichia coli*

Chemotaxis is regulated by chemoreceptors located in the cytoplasmic membrane or periplasm of the bacterium bind chemical attractants or repellents. In most cases, this leads to either the methylation or demethylation of methyl-accepting chemotaxis proteins (MCPs) that in turn, eventually trigger either a counterclockwise or clockwise rotation of the flagellum. An increasing concentration of attractant or decreasing concentration of repellent (both conditions beneficial) causes less tumbling and longer runs; a decreasing concentration of attractant or increasing concentration of repellent (both conditions harmful) causes normal tumbling and a greater chance of reorienting in a "better" direction. As a result, the organism's net movement is toward the optimum environment..

**Significance of Flagella in the Initiation of Body Defense**

**Initiation of Innate Immunity**

To protect against infection, one of the things the body must initially do is detect the presence of microorganisms. The body does this by recognizing molecules unique to microorganisms that are not associated with human cells. These unique molecules are called pathogen-associated molecular patterns or PAMPs. (Because all microbes, not just
pathogenic microbes, possess PAMPs, pathogen-associated molecular patterns are sometimes referred to as microbe-associated molecular patterns or MAMPs.)

The protein flagellin in bacterial flagella is a PAMP that binds to pattern-recognition receptors or PRRs on a variety of defense cells of the body and triggers innate immune defenses such as inflammation, fever, and phagocytosis.

For More Information: Pathogen-Associated Molecular Patterns (PAMPs) from Unit 5

For More Information: Pattern-Recognition Receptors from Unit 5

Initiation of Adaptive Immunity

Proteins associated with bacterial flagella function as antigens and initiate adaptive immunity. An antigen is defined as a molecular shape that reacts with antibody molecules and with antigen receptors on lymphocytes. We recognize those molecular shapes as foreign or different from our body's molecular shapes because they fit specific antigen receptors on our B-lymphocytes and T-lymphocytes, the cells that carry out adaptive immunity.

The actual portions or fragments of an antigen that react with antibodies and with receptors on B-lymphocytes and T-lymphocytes are called epitopes. An epitope is typically a group of 5-15 amino acids with a unique shape that makes up a portion of a protein antigen, or 3-4 sugar residues branching off of a polysaccharide antigen. A single microorganism has many hundreds of different shaped epitopes that our lymphocytes can recognize as foreign and mount an adaptive immune response against.

The body recognizes an antigen as foreign when epitopes of that antigen bind to B-lymphocytes and T-lymphocytes by means of epitope-specific receptor molecules having a shape complementary to that of the epitope. The epitope receptor on the surface of a B-lymphocyte is called a B-cell receptor and is actually an antibody molecule. The receptor on a T-lymphocyte is called a T-cell receptor (TCR).

There are two major branches of the adaptive immune responses: humoral immunity and cell-mediated immunity.

1. Humoral immunity: Humoral immunity involves the production of antibody molecules in response to an antigen and is mediated by B-lymphocytes. Through a variety of mechanisms, these antibodies are able to remove or neutralize microorganisms and their toxins after binding to their epitopes. For example, antibodies made against flagellar antigens can stick bacteria to phagocytes, a process called opsonization. They can also interfere with bacterial motility.

2. Cell-mediated immunity: Cell-mediated immunity involves the production of cytotoxic T-lymphocytes, activated macrophages, activated NK cells, and cytokines in response to an antigen and is mediated by T-lymphocytes. These defense cells help to remove infected cells and cancer cells displaying foreign epitopes.

Adaptive immunity will be discussed in greater detail in Unit 6.

For More Information: Review of antigens and epitopes from Unit 6
Significance of Motility to Bacterial Pathogenicity

Motility and chemotaxis probably help some intestinal pathogens to move through the mucous layer so they can attach to the epithelial cells of the mucous membranes. In fact, many bacteria that can colonize the mucous membranes of the bladder and the intestines are motile. Motility probably helps these bacteria move through the mucus in places where it is less viscous.

Motility and chemotaxis also enable spirochetes to move through viscous environments and penetrate cell membranes. Examples include *Treponema pallidum* (inf), *Leptospira* (inf), and *Borrelia burgdorferi* (inf). Because of their thinness, their internal flagella (axial filaments), and their motility, spirochetes are more readily able to penetrate host mucous membranes, skin abrasions, etc., and enter the body. Motility and invasins may also enable the spirochetes to penetrate deeper in tissue and enter the lymphatics and bloodstream and disseminate to other body sites.

Electron micrograph of *Treponema pallidum* invading a host cell.

This will be discussed in more detail under Bacterial Pathogenesis in Unit 3.

For More Information: The Ability to Contact Host Cells from Unit 3

For More Information: The Ability to Invade Host Cells from Unit 3

Highlighted Bacterium: *Treponema pallidum*

Click on this link, read the description of *Treponema pallidum*, and be
able to match the bacterium with its description on an exam.

Concept map for Bacterial Flagella

Medscape article on infections associated with organisms mentioned in this Learning Object. Registration to access this website is free.

- *Treponema pallidum*
- *Leptospira*
- *Borrelia burgdorferi*
- *Helicobacter pylori*

Summary

1. Many bacteria are motile and use flagella to swim through liquid environments.
2. The basal body of a bacterial flagellum functions as a rotary molecular motor, enabling the flagellum to rotate and propel the bacterium through the surrounding fluid.
3. Bacterial flagella appear in several arrangements, each unique to a particular organism.
4. Motility serves to keep bacteria in an optimum environment via taxis.
5. Taxis refers to a motile response to an environmental stimulus enabling the net movement of bacteria towards some beneficial attractant or away from some harmful repellent.
6. Most bacterial flagella can rotate both clockwise and counterclockwise enabling to stop and change direction.
7. The protein flagellin that forms the filament of bacterial flagella functions as a pathogen-associated molecular pattern or PAMP that binds to pattern-recognition receptors or PRRs on a variety of defense cells of the body to trigger innate immune defenses.
8. Motility and chemotaxis probably help some intestinal pathogens to move through the mucous layer so they can attach to the epithelial cells of the mucous membranes and colonize the intestines.
9. Motility enables some spirochetes to penetrate deeper in tissue and enter the lymphatics and bloodstream and disseminate to other body sites.

Questions

Study the material in this section and then write out the answers to these questions. Do not just click on the answers and write them out. This will not test your understanding of this tutorial.

1. Describe the basic structure of a bacterial flagellum and state its function. *(ans)*
2. Define taxis. (ans)

3. Matching:

   _____ surrounded by flagella (ans)

   _____ a single flagellum at both ends (ans)

   _____ periplasmic flagella found only in spirochetes (ans)
   
   A. monotrichous  
   B. amphitrichous  
   C. lophotrichous  
   D. peritrichous  
   E. axial filaments

4. State how bacterial flagella may play a role in the initiation of innate immune defenses. (ans)

5. Briefly describe how bacterial flagella and chemotaxis may play a role in the pathogenocity of some bacteria. (ans)

6. Multiple Choice (ans)

Contributors

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